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Glacial geomorphology of the Skálafellsjökull foreland, Iceland: a case study of "annual" moraines

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Glacial geomorphology of the Skálafellsjökull foreland, Iceland: a case study of "annual" moraines

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Glacial geomorphology of the Skálafellsjökull foreland, Iceland: a case study of "annual" moraines

Abstract

Small-scale recessional ("annual") moraines are a characteristic signature of the active temperate glacial landsystem. These "annual" moraines represent a potentially valuable terrestrial climate archive, and may provide valuable insights into glacier dynamics. This paper presents detailed glacial geomorphological maps of "annual" moraines on the foreland of Skálafellsjökull, SE Iceland. Geomorphological maps have been produced at a scale of 1:3,750 based on 2006 aerial photographs and 2012 satellite imagery. Using UAV-captured imagery, large-scale sample maps of two selected areas of the glacier foreland have also been produced at scales of 1:850 and 1:750, respectively. Desk- and field-based mapping reveals suites of recessional ("annual") moraines distributed across the glacier foreland, often found in close association with flutings. Moraines on the foreland typically display distinctive "sawtooth" planform geometries, with complexities in the pattern occurring due to localised superimposition. The inventory of glacial geomorphological maps presented here provides a framework for subsequently exploring the characteristics of the "annual" moraines and recent ice-marginal fluctuations at Skálafellsjökull.

Keywords: glacial geomorphology; remote sensing; "annual" moraines; active temperate glacial landsystem; Skálafellsjökull; Iceland

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1. Introduction

Annual ice-marginal fluctuations at many Icelandic glaciers are manifest in the form of annual (push/squeeze) moraines (e.g. Price, 1970; Sharp, 1984; Krüger, 1995; Evans and Twigg, 2002), a characteristic signature of the active temperate glacial landsystem (Evans, 2003, 2005; Evans and Orton, 2015). Annual moraine formation occurs at the ice-margin during a period when forward ice-front movement exceeds the negligible ablation during the winter (Lukas, 2012; Bradwell et al., 2013). Long sequences of annual moraines form when ice-front recession during the summer (ablation season) outstrips advance during the winter (accumulation season) over the course of a number of years (Boulton 1986; Bennett 2001). Long sequences of annual moraines potentially contain a seasonal signature of glacier response to climatic fluctuations, and have been associated with periods of elevated ablation-season temperature (Sharp, 1984; Krüger, 1995; Bradwell, 2004; Beedle et al., 2009; Bradwell et al., 2013). Given the potential of these features as a terrestrial climate archive, detailed examination of the characteristics of annual moraines on the forelands of Icelandic glaciers could yield valuable insights into the nature of, and controls on, recent ice-marginal retreat. During the past decade Icelandic glaciers have exhibited accelerating rates of ice-marginal retreat and mass loss (e.g. Sigurðsson et al., 2007; Björnsson et al., 2013). Understanding this current rapid glacier change is crucial to placing current atmospheric warming and associated glacier retreat in a broader context. This study presents detailed mapping of "annual" moraines on the foreland of Skálafellsjökull, SE Iceland, with the intention of providing a framework to examine: (i) the moraine characteristics (geomorphology, genesis and chronology) in detail; and (ii) patterns and rates of ice-marginal retreat at this outlet glacier. These "annual" moraines have previously been argued to form on an annual basis through seasonally-driven ice-marginal processes (cf. Sharp, 1984), and the detailed mapping will therefore also provide a basis for re-examining this concept.

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2. Study site and previous work

2.1 Study site

Skálafellsjökull, a non-surging outlet of the southeastern margin of the Vatnajökull ice-cap in SE Iceland, flows for ~25 km from the Breiðabunga plateau in eastern Vatnajökull (Figure 1). The glacier descends steeply from the lava plateau onto a low elevation foreland, where it splays out to form a piedmont lobe. The current ice-margin terminates at an altitude of ~60 m a.s.l. on the Hornafjördur coastal plain (McKinzey et al., 2004; Evans and Orton, 2015). At its northern margin, the glacier is topographically confined by the Hafrafellsháls mountain spur, which reaches a maximum elevation of ~1008 m a.s.l. (Evans and Orton, 2015). The contemporary Skálafellsjökull ice-margin is fronted by two proglacial lakes, the largest situated on Heinabergsvötn (Figure 1c), and a smaller proglacial lake at the southeastern sector of the ice-margin.

Documentary evidence and maps indicate that Skálafellsjökull formerly coalesced with the neighbouring Heinabergsjökull, and they remained confluent until sometime between 1929 and 1945 (cf. Thórarinsson, 1943; Hannesdóttir et al., 2014, and references therein). Ice-front measurements conducted at the glacier since the 1930s indicate Skálafellsjökull underwent similar fluctuations to other non-surge-type Vatnajökull outlet glaciers (e.g. Sigurðsson, 1998). Since the 1970s, however, measurements have been sporadic, limiting understanding of glacier change at Skálafellsjökull during this period. Thus, the sequences of recessional ("annual") moraines previously identified on the Skálafellsjökull foreland (Sharp, 1984; Evans and Orton, 2015) offer the opportunity to gain important insights into ice-frontal fluctuations.

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2.2 Previous mapping

Skálafellsjökull has been the subject of a number of studies, including the investigation of the glacial landsystem as whole (Evans and Orton, 2015), component sediment-landform assemblages (Sharp, 1984; Dowdeswell and Sharp, 1986; Evans, 2000) and the timing of LIA maxima (e.g. Gordon and Sharp, 1983; Evans et al., 1999; McKinzey et al., 2004). In a recent study, Evans and Orton (2015) mapped the surficial geology and glacial geomorphology of the Skálafellsjökull foreland, and neighbouring Heinabergsjökull foreland. Evans and Orton (2015) established that the Skálafellsjökull glacier foreland constitutes a landsystem imprint of actively retreating temperate glaciers in a mountain environment with a high glaciofluvial sediment yield. Moreover, the landsystem is characterised by the three diagnostic depositional domains of the active temperate landsystem previously identified for Icelandic piedmont lobes: marginal morainic, subglacial and glaciofluvial/glaciolacustrine (Krüger, 1994; Evans and Twigg, 2002; Evans, 2003, and references therein). The Skálafellsjökull glacier foreland also contains site-specific sediment-landform assemblages, notably overridden kame terraces on the southern part of the foreland. The survival of kame terraces is unusual and therefore the fluted kame terraces at Skálafellsjökull provide an important modern analogue for studies on palimpsest glacial landscapes, which are traditionally assumed to be produced by cold-based conditions in contrast to the wet-based conditions at Skálafellsjökull (e.g. Forman et al., 1987; Hättestrand and Stroeven, 2002; Landvik et al., 2005; Davis et al., 2006). The combined landform record of Skálafellsjökull and Heinabergsjökull constitutes a modern glacial landsystem analogue for active temperate piedmont lobes associated with the construction of large outwash heads fed by high glaciofluvial sediment yields (Evans and Orton, 2015).

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Research focused on the marginal morainic domain of the Skálafellsjökull foreland has previously been conducted by Sharp (1984). The study specifically examined a sequence of "annual" moraines within the southern part of the foreland, located in an area of roches moutonnées and a discontinuous sheet of fluted subglacial traction till (*sensu* Evans et al., 2006; Sharp, 1984; Evans and Orton, 2015). Sedimentological investigations by Sharp (1984) identified four process combinations, argued to be forming moraine ridges on an annual basis at the southeastern sector of the ice-margin. However, no detailed, large-scale mapping of the intricate details of the "annual" moraines was presented.

2.3 Purpose of the mapping

The rationale for producing detailed maps of the "annual" moraines on the foreland of Skálafellsjökull was twofold: (i) to provide context for examining the characteristics of these features (moraine geomorphology, sedimentology and chronology) in detail; and (ii) to provide a framework for investigating recent ice-marginal fluctuations using moraine spacing. Importantly, the mapping, combined with additional sedimentological and chronological analyses, will allow a re-examination of the concept of annual moraine formation at Skálafellsjökull (cf. Sharp, 1984; Evans and Orton, 2015). The mapping also aimed to build on the previous small-scale landsystem mapping undertaken by Evans and Orton (2015). Individual maps have been produced at a scale of 1:3,750 based on the 2006 aerial photographs (Map 1) and 2012 satellite imagery (Map 2), providing a visual demonstration of recent ice-marginal retreat and the evolution of the glacier foreland. In addition to these two smaller-scale maps, detailed sample mapping of "annual" moraines has been conducted based on hillshaded relief models generated from a 2013 high-resolution DEM (Maps 3 and 4), allowing the complexity of "annual" moraine distribution and geomorphology to be examined. These large-scale maps have been produced at scales of

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1:850 (Map 3) and 1:750 (Map 4), respectively. As the focus of the mapping was on the intricate details of the "annual" moraines, the maps do not include detailed mapping of the surficial geology. An indication of the distribution and coverage of glaciofluvial sediments is presented, though this mapped unit has been simplified so as not to detract from the detail of the mapped moraines. As highlighted above, mapping of the surficial geology has been presented by Evans and Orton (2015).

3. Methods

3.1 Remote sensing datasets and image preparation

For the purposes of glacial geomorphological mapping, four remote sensing datasets were acquired (Figure 2). High-resolution scans of 2006 colour aerial photographs with a resolution of 0.41 m GSD (Ground Sampled Distance) per pixel were obtained from the Icelandic survey company *Loftmyndir ehf*, whilst multispectral (8-band) and panchromatic satellite imagery captured by the WorldView-2 satellite sensor in June 2012 were acquired from *European Space Imaging*. The multispectral (8-band) satellite imagery and panchromatic images have resolutions of 2.0 m GSD and 0.5 m GSD, respectively. In addition, a further high-resolution remote sensing dataset has been used for mapping: specifically a Digital Elevation Model (DEM) with a spatial resolution of 0.09 m, derived from imagery captured using an Unmanned Aerial Vehicle (UAV) during aerial surveys of the Skálafellsjökull foreland in 2013 (see Hackney and Clayton, 2015). The images were taken using a fixed-wing QuestUAV 200 craft equipped with a mirrorless camera (Panasonic Lumix LX5 camera with 10.1 megapixel, 1/1.63 inch high-sensitivity CCD). Surveys were flown at an altitude of 100 m, yielding images with a resolution of 0.05 m GSD. A total of 1,980 images were used to construct the DEM, selected on the basis of image quality and coherence of lighting. The final dataset of images used for processing had an approximate

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photograph endlap of 80% and sidelap of 60%. However, the dataset does not provide complete coverage of the Skálafellsjökull foreland, covering ~2 km^2 of the total area (~4.9 km^2) mapped. Thus, the 2006 aerial photographs and 2012 satellite imagery were largely used in the composition of the smaller-scale geomorphological maps (Maps 1 and 2).

Digital photogrammetric processing was conducted to remove the varying degrees of geometric distortion inherent within aerial photographs (Lillesand et al., 2008; Campbell and Wynne, 2011). For this purpose, both the 2006 aerial photographs and UAV-captured imagery were processed in *Agisoft PhotoScan Professional Edition*, which utilises a *Structure-from-Motion* (SfM) approach. SfM operates under the same basic principles as stereoscopic photogrammetry, namely that 3D structure can be reconstructed from a series of overlapping, offset two-dimensional images. However, it differs fundamentally from conventional photogrammetry in that the geometry of the scene, camera positions and orientation are solved automatically without the need to specify *a priori* a network of targets with known 3D positions (Westoby et al., 2012). Instead, these are solved simultaneously using an iterative bundle adjustment procedure, based on a database of features automatically extracted from a set of multiple overlapping images (Snavely, 2008; Westoby et al., 2012; Ryan et al., 2015). Position information can then be introduced after model production in an arbitrary coordinate system, meaning that errors in ground control points (GCPs) will not propagate in the DEM.

The first stage of processing in *Agisoft Photoscan* involves image alignment. The software implements SfM algorithms to track features through a sequence of overlapping images in order to estimate the relative location of camera positions for each image and generate a 3D point-cloud of the tracked features (cf. Ryan et al., 2015, for further details). The point-cloud

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can subsequently be optimised and georeferenced using GCPs and/or using onboard telemetry data. Following image alignment, a multi-view reconstruction algorithm is applied to produce a 3D polygon mesh based on pixel values (Verhoeven, 2011; Ryan et al., 2015). These 3D models can then be transformed and exported as DEMs and orthophotos. Using this approach raster, grid DEMs with cell sizes of 0.41 m and 0.09 m were generated using the 2006 aerial photographs and 2013 UAV-imagery, respectively. An orthophoto mosaic of the foreland, with a cell size of 0.41 m, was also produced using the 2006 model for the purposes of landform mapping.

Positional ground control for the 2006 model was collected in the field using a Leica 1200 differential Global Positioning System (dGPS) between May and June 2014. The collected ground control points (GCPs) were processed using the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP: http://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en) tool, with the corrections then applied in *Leica Geo Office 8.3*. The Coordinate Conversion and Datum Transformation in Iceland (cocodat[i]: http://cocodati.lmi.is/cocodati/cocodat-i.jsp) tool was then employed to generate orthometric heights for the GCPs and to convert the coordinates to UTM projected coordinates for zone 28N. Orthometric heights generated using the cocodat[i] tool are based on the ISN93 datum, ellipsoid GRS80 and applies the new Icelandic geoid model. For practical purposes GRS80 and WGS1984 can be considered approximately equal, since there is a difference of only 0.1 mm in the semi-minor axis (cf. Rennen, 2004). The point-cloud generated in *Agisoft PhotoScan* using the 2006 aerial photographs was optimised and georeferenced to WGS 1984 / UTM Zone 28N (ESPG: 32628) using the processed GCPs (n = 50). This coordinate system is compatible with the system currently employed by *Landmælingar Íslands* (National Land Survey of Iceland) in the production of Icelandic maps. The UAV surveys were undertaken in

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conjunction with a Leica dGPS deployed in Real-Time Kinematic (RTK) mode to allow georeferencing of the UAV-captured imagery (see Hackney and Clayton, 2015). Positional information for the UAV-imagery was provided by 15 GCPs located in a grid network across the surveyed area, with the model also georeferenced to WGS 1984 / UTM Zone 28N.

The satellite imagery obtained from *European Space Imaging* was purchased as *Ortho Ready Standard* and had been projected to UTM Zone 28N, spheroid WGS1984. The supplied imagery was orthorectified in *ArcMap 10.2* using the DEM generated from the 2006 aerial photographs. Following orthorectification, a pan-sharpened, natural colour multispectral image (3-band: Blue, Red Green) with a resolution of 0.5 m GSD per pixel was generated using the IHS method in *ArcMap* (Figure 3). The IHS method uses Intensity, Hue and Saturation Colour to merge the high-resolution panchromatic data (0.5 m GSD) with medium-resolution multispectral data (2.0 m GSD) in order to produce a multispectral image with higher-resolution properties.

For meaningful graphical and analytical purposes, the DEM data were converted into hillshaded relief models using *Spatial Analyst* in *ArcMap*. Hillshaded relief models were produced using an illumination angle of 30° and azimuths set at orthogonal positions of 45° and 315° (Figure 4). These properties have been extensively used in generating hillshaded relief models for the purposes of glacial geomorphological mapping and have been suggested as optimal settings for visualisation (e.g. Smith and Clark, 2005; Chen and Rose, 2008; Hughes et al., 2010; Boston, 2012; Pearce et al., 2014). Displaying the DEM data as hillshaded relief models with differing azimuths avoids azimuth bias and permits geomorphological features to be viewed under different lighting conditions, which can increase the visibility of subtle landforms (Smith and Clark, 2005; Pearce et al., 2014).

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3.2 Map production

Detailed glacial geomorphological mapping was conducted from the imagery discussed above, combined with field investigations conducted in May and June 2014 to ground truth the desk-based mapping. This approach of applying multiple remote sensing datasets, augmented by field-based geomorphological investigations, has been extensively applied in the context of both glacierised and glaciated landscapes, encompassing a variety of geographical locations (e.g. Bennett et al., 2010; Boston, 2012; Bradwell et al., 2013; Reinardy et al., 2013; Brynjólfsson et al., 2014; Darvill et al., 2014; Evans et al., 2014, submitted; Jónsson et al., 2014; Pearce et al., 2014). The application of both the interpretation of remote sensing data and field surveys permits a holistic approach to mapping, wherein the advantages of each method can be combined to produce an accurate map with robust genetic interpretations (Brown et al., 2011; Boston, 2012).

Overlays of geomorphological features were digitally drawn in *ArcMap 10.2* using the remote sensing data, with individual vector layers created for each geomorphological feature. The initial interpretation of the remote sensing data and on-screen digitisation was then checked in the field. In order to enhance the accuracy of mapping and reduce errors which may arise from misinterpretation of features, examination of the remote sensing data was conducted both prior to and after the field investigations (cf. Lukas and Lukas, 2006; Boston, 2012; Pearce et al., 2014). The final digitised features were then exported to *Adobe Illustrator CC* for final editing and map production, along with a contour layer calculated at 20 m intervals using *Spatial Analyst* in *ArcMap* and the 2006 DEM to derive the elevation data. Following in the tradition of previous glacial geomorphological maps of Icelandic glacier

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forelands, the glacier surface is represented on the maps by a mask generated directly from the processed imagery (cf. Evans, 2009).

4. Results

4.1 Moraine distribution and geomorphology

Glacial geomorphological mapping reveals a series of recessional ("annual") moraines distributed across the Skálafellsjökull foreland, with a total of 3,201 moraine fragments mapped on the glacier foreland based on the 2012 satellite imagery. Long, largely uninterrupted sequences of moraines occur on the northern and central parts of the glacier foreland. Additionally, numerous "annual" moraines are evident in close proximity to the southeastern sector of the Skálafellsjökull margin. Comparison of the 2006 and 2012 maps of the glacier foreland reveals that moraine formation has occurred at both the southeastern and northeastern sectors of the Skálafellsjökull ice-margin, with 281 moraine fragments formed during this period. These individual moraine fragments form part of longer, discontinuous ridges that appear to reflect the geometry of the ice-margin. The mapping also indicates that this period of moraine formation coincides with a phase of substantial glacier retreat and ice-marginal lake expansion.

Following journal guidelines, detailed analysis of "annual" moraine properties are not presented here, but some characteristic features are briefly outlined. Further detailed analysis will be presented in a subsequent paper. The moraines typically take the form of discontinuous ridges, consisting of a number of smaller fragments which form part of longer chains (Figure 5). Crest-to-crest spacing (or longitudinal) spacing between individual chains of "annual" moraines ranges from ~5 m to 60 m on the Skálafellsjökull foreland. In planform, moraine ridges on the Skálafellsjökull foreland exhibit a distinctive "sawtooth" or crenulate

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pattern, with teeth pointing in a down-ice direction and notches pointing upglacier (Figure 6; cf. Matthews et al., 1979). Teeth exhibit maximum wavelengths and amplitudes of ~50 m and ~39 m, respectively, whilst notches exhibit maximum wavelengths and amplitudes of ~47 m and ~41 m. Complexities in the general planview geometry occur locally, with individual moraine ridges exhibiting bifurcations and cross-cutting patterns. The large-scale, sample mapping of moraines in two selected areas (Maps 3 and 4) of the glacier foreland, based on UAV-captured imagery, provides a clear visualisation of the characteristic planform geometry and local complexities in this pattern. The "annual" moraines on the Skálafellsjökull foreland are typically asymmetrical in cross-section, with cross-profiles displaying shorter, steeper distal slopes and longer, gently-sloping ice-proximal surface slopes. Individual moraines have heights ranging from ~0.2 m to 1.5 m, with moraine width being between ~2 m and 18 m.

4.2 Associated glacial geomorphological features

Moraines on the Skálafellsjökull foreland are frequently found in close association with flutings (Figure 7), which may extend on to the ice-proximal slopes of moraines in places. Mapped flutings range in length from 7 m to 201 m, with a mean value of 42.8 m (n = 951; 2012 imagery). On the reverse basalt bedrock slope near the southeastern sector of the Skálafellsjökull margin, "annual" moraines and flutings are also found in association with an abundance of roches moutonnées: flutings often extend from the lee-side faces of roches moutonnées. This area of the glacier foreland is also characterised by a number of recessional meltwater channels and a contemporary meltwater stream running along the ice-margin. Locally, meltwater accumulates along parts of the southeastern margin to form a small ice-marginal lake. At the time of the field surveys (May–June 2014), moraines in close proximity to the contemporary ice-margin could be found partially submerged by ponded and slow-

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moving meltwater. The close association of flutings and "annual" moraines on the Skálafellsjökull foreland suggests the formation of these geomorphological features may be intimately linked, as has previously been suggested at Icelandic glaciers (cf. Boulton, 1976; Boulton and Hindmarsh, 1987; Benn, 1994; Evans and Twigg, 2002; Evans, 2003).

5. Summary and conclusions

Geomorphological mapping in this study, through a combination of desk- and field-based mapping, has resulted in the production of detailed, high-resolution glacial geomorphological maps showing the distribution of "annual" moraines and associated geomorphological features on the Skálafellsjökull foreland. The geomorphological mapping revealed a series of small-scale recessional ("annual") moraines, with long sequences of moraines occurring on the northern and central parts of the glacier foreland. These "annual" moraines display distinctive "sawtooth" planform geometries (cf. Price, 1970; Matthews et al., 1979; Bradwell, 2004). Complexities in the general pattern occur locally, with individual moraines exhibiting bifurcations and cross-cutting patterns. The inventory of geomorphological maps produced in this study provides a framework for subsequently exploring moraine chronology and sedimentology, from which recent ice-marginal fluctuations of Skálafellsjökull can be examined.

This study has also demonstrated potential of imagery captured using an Unmanned Aerial Vehicle (UAV) for the purposes of high-resolution mapping of small-scale geomorphological features. The acquisition of imagery using UAVs represents a potentially effective and low-cost technique for producing high-resolution, 3D georeferenced data (e.g. d'Oleire-Oltmanns et al., 2012; Hugenholtz et al., 2012, 2013; Lucieer et al., 2014) but its application in glaciology and glacial geomorphology has so far been limited (e.g. Whitehead et al., 2013;

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Ryan et al., 2015; Evans et al., submitted). In the context of contemporary glacial environments, UAV imagery represents a potentially valuable tool for repeat surveying and monitoring, allowing further insights into ice-frontal fluctuations and proglacial landscape evolution to be gained.

Software

Image processing was conducted in *Agisoft Photoscan Professional Edition*, whilst processing of GPS data was performed in *Leica Geo Office 8.3*. Desk-based geomorphological mapping was undertaken in *ESRI ArcMap 10.2*, with the mapping exported to *Adobe Illustrator CC* for final editing and map production.

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For Peer Review Only

List of Figures

Figure 1. (a) Field photograph of Skálafellsjökull descending from the Breiðabunga plateau in eastern Vatnajökull (27.05.14). (b) Map showing the location of Skálafellsjökull, SE Iceland. (c) Skálafellsjökull descends onto Hornafjördur coastal plain where it terminates as a piedmont lobe. The contemporary ice-margin is fronted by a proglacial lake on Heinabergsvötn.

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Figure 3. Comparison of the processed satellite imagery used in this research. (a) Panchromatic satellite image (0.5 m GSD). (b) Multispectral satellite image (2.0 m GSD). (c) Pansharpened 3-band natural colour image (0.5 m GSD).

Figure 4. Extracts from hillshaded relief models showing "annual" moraines on the foreland of Skálafellsjökull. The models are derived from the UAV-captured imagery. (a) Hillshaded relief model generated using an illumination angle of 30° and an azimuth of 45°. (b) Hillshaded relief model generated using an illumination angle of 30° and an azimuth of 315°. The difference in appearance of the "annual" moraines between the two models is apparent, demonstrating the value of visualising the data with different azimuths.

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Figure 5. Histogram and summary statistics of mapped moraine lengths for the entire dataset. Box-and-whisker plots show the 25th and 75th percentiles (grey box), and the 5th and 95th percentiles (whisker ends). The mean (horizontal line) is also shown.

Figure 6. Field photograph showing the characteristic "sawtooth" planform of moraines on the Skálafellsjökull foreland.

Figure 7. Field photograph across the southern part of the Skálafellsjökull foreland showing the close association of moraines and flutings.

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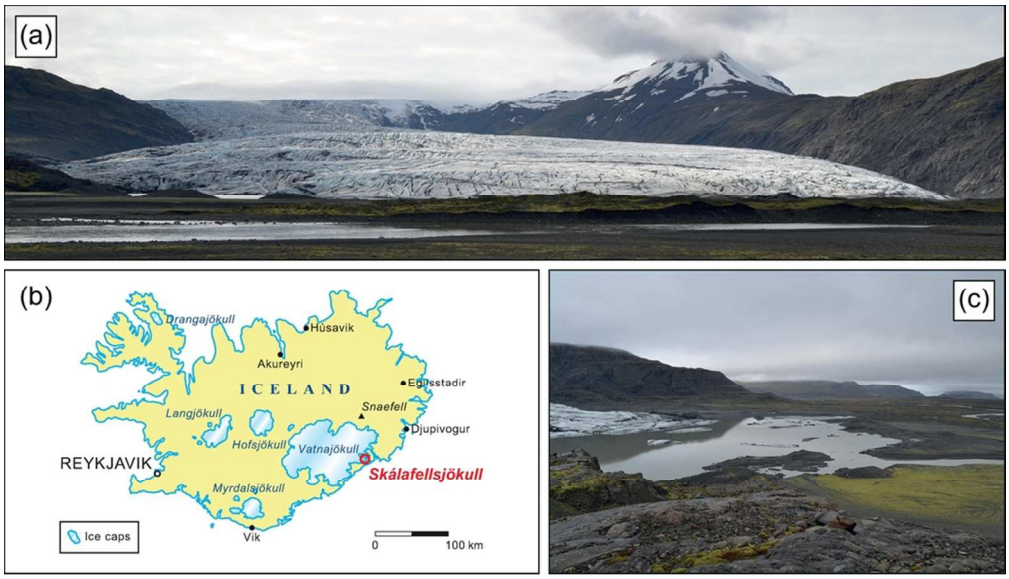

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88x50mm (300 x 300 DPI)

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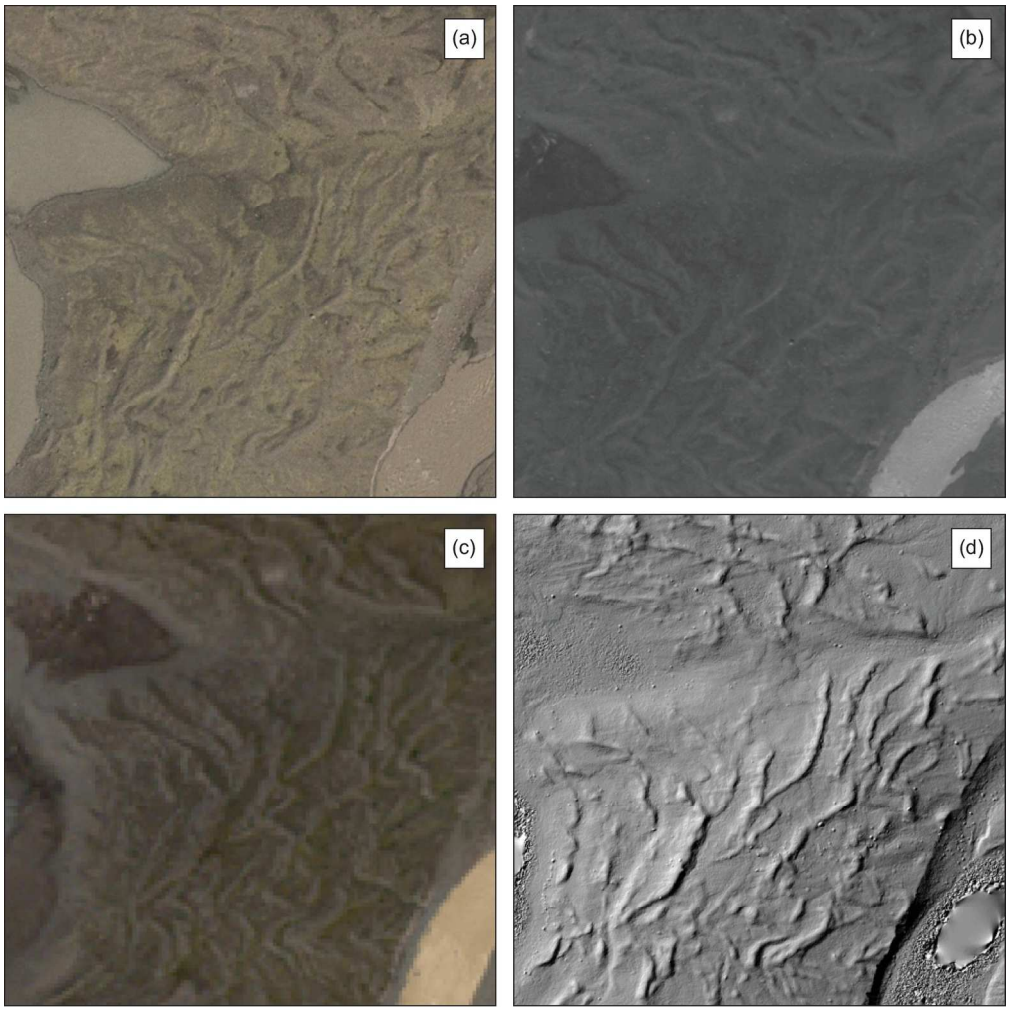

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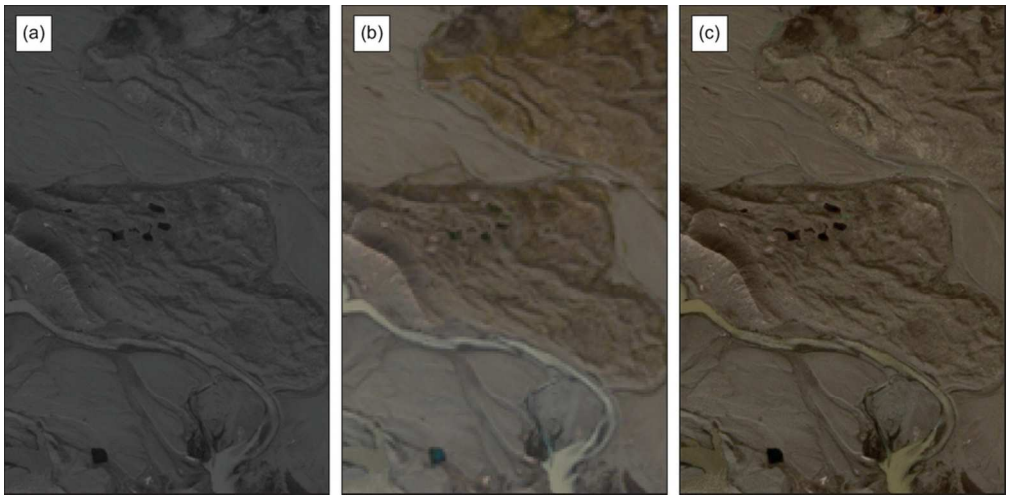

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93x45mm (300 x 300 DPI)

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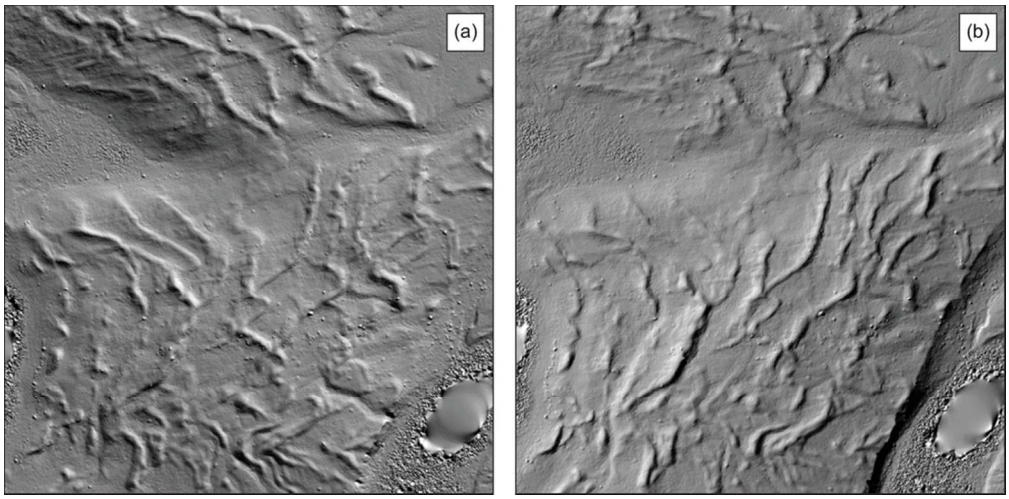

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90x44mm (300 x 300 DPI)

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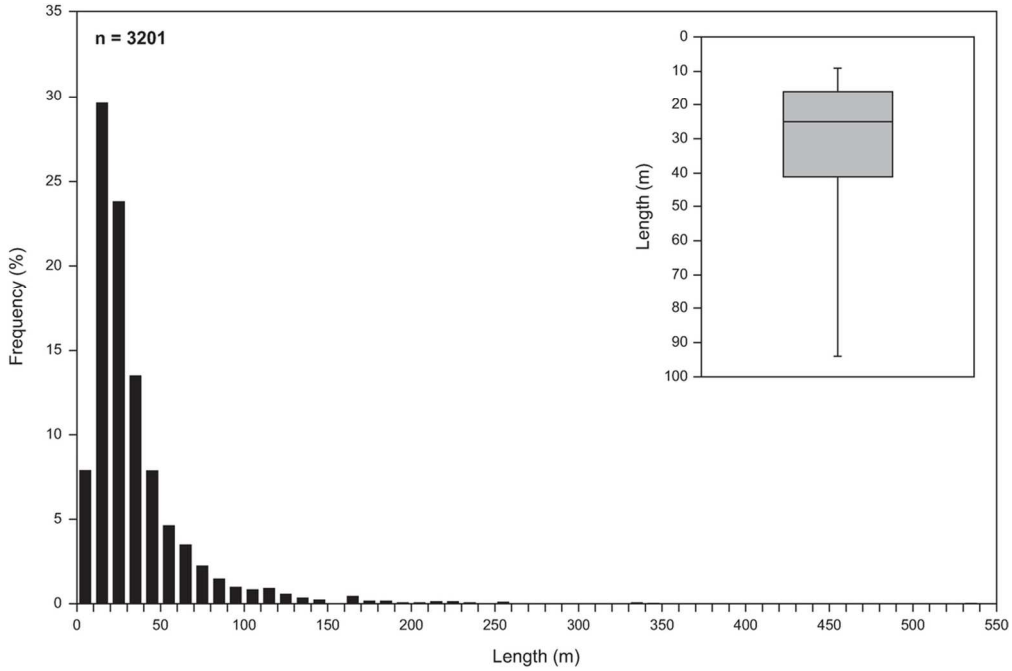

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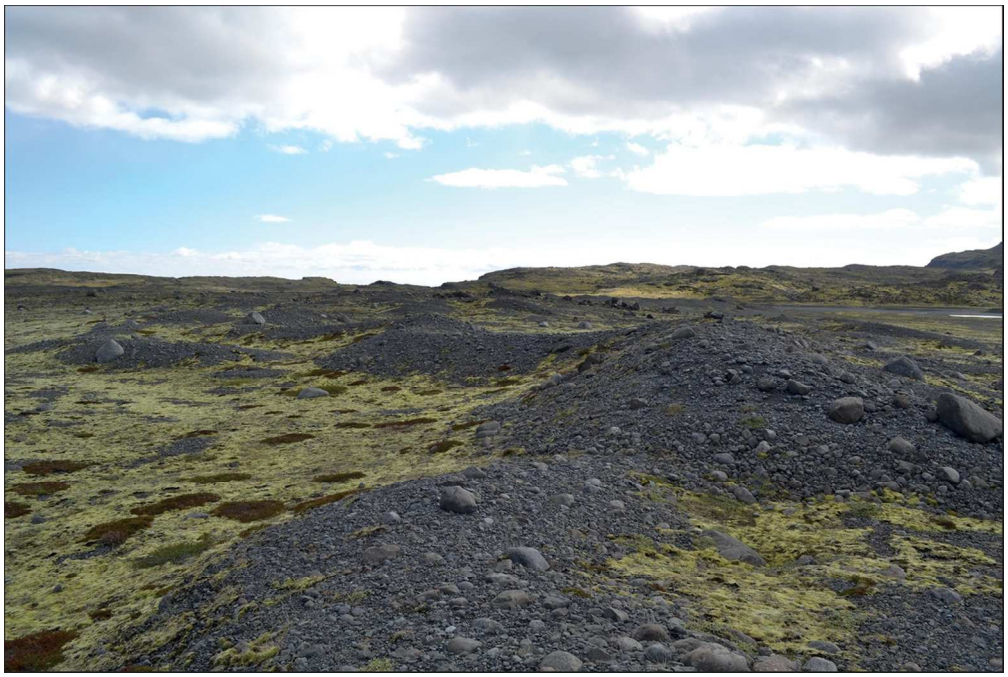

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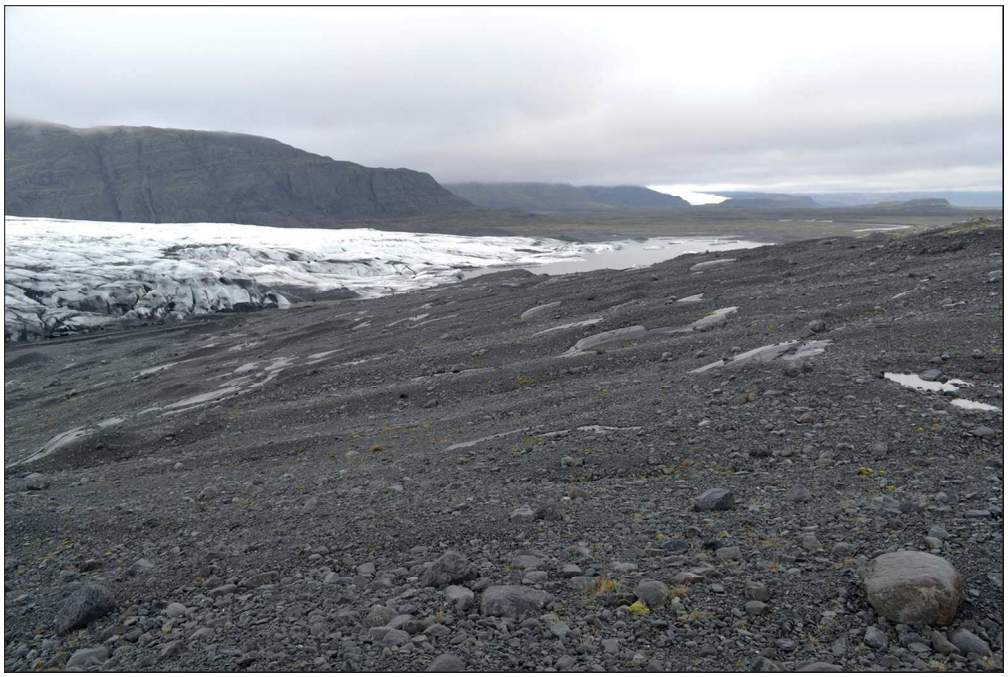

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115x77mm (300 x 300 DPI)

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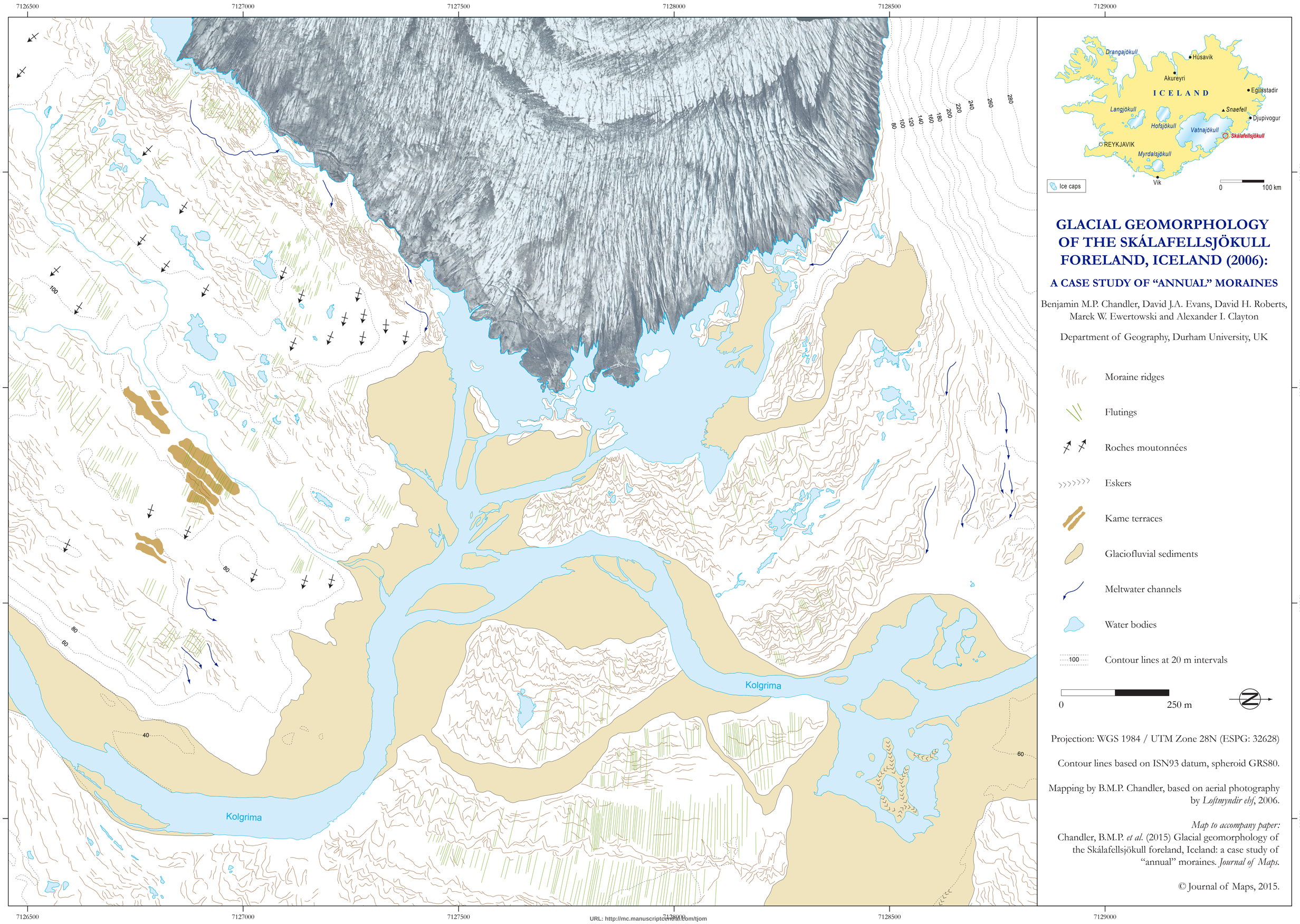

GLACIAL GEOMORPHOLOGY OF THE SKÁLAFELLSJÖKULL FORELAND, ICELAND (2006):

A CASE STUDY OF "ANNUAL" MORAINES

Benjamin M.P. Chandler, David J.A. Evans, David H. Roberts, Marek W. Ewertowski and Alexander I. Clayton

Department of Geography, Durham University, UK

- Moraine ridges
- Flutings
- Roches moutonnées
- Eskers
- Kame terraces
- Glaciofluvial sediments
- Meltwater channels
- Water bodies
- 100 Contour lines at 20 m intervals

0 250 m

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Projection: WGS 1984 / UTM Zone 28N (ESPG: 32628)

Contour lines based on ISN93 datum, spheroid GRS80.

Mapping by B.M.P. Chandler, based on aerial photography by *Loftmyndir ehf*, 2006.

Map to accompany paper:
Chandler, B.M.P. *et al.* (2015) Glacial geomorphology of the Skálafellsjökull foreland, Iceland: a case study of "annual" moraines. *Journal of Maps*.

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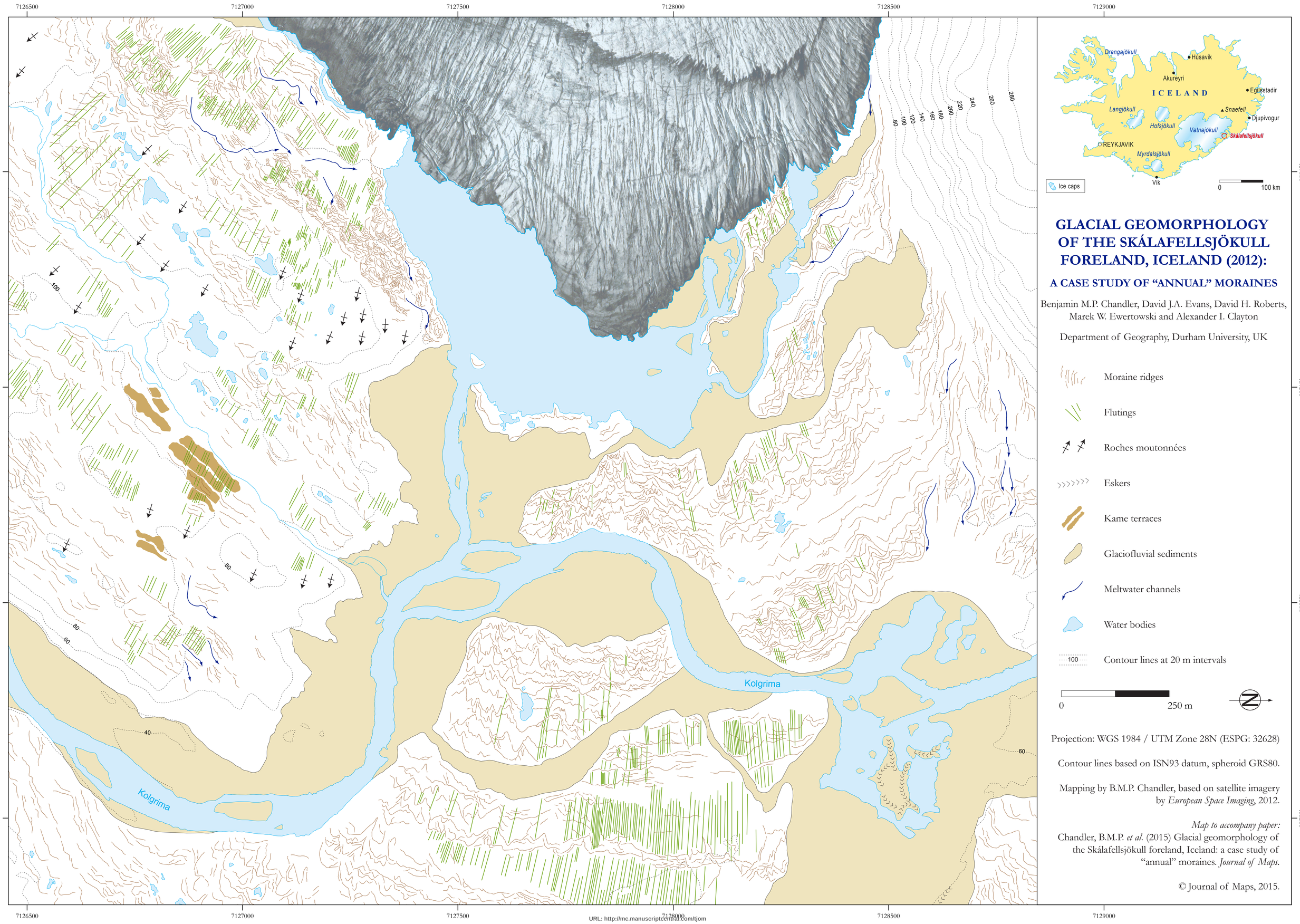

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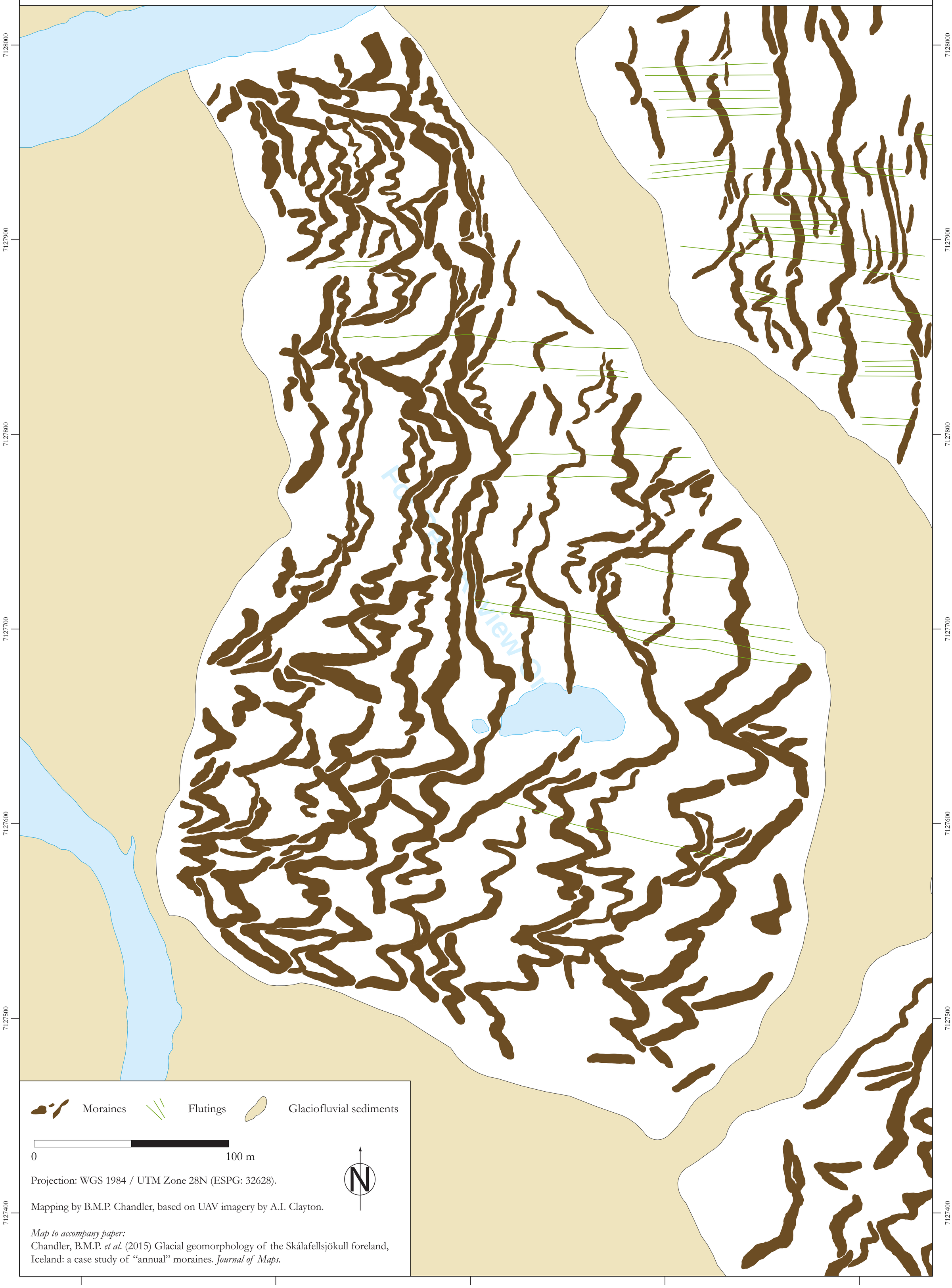

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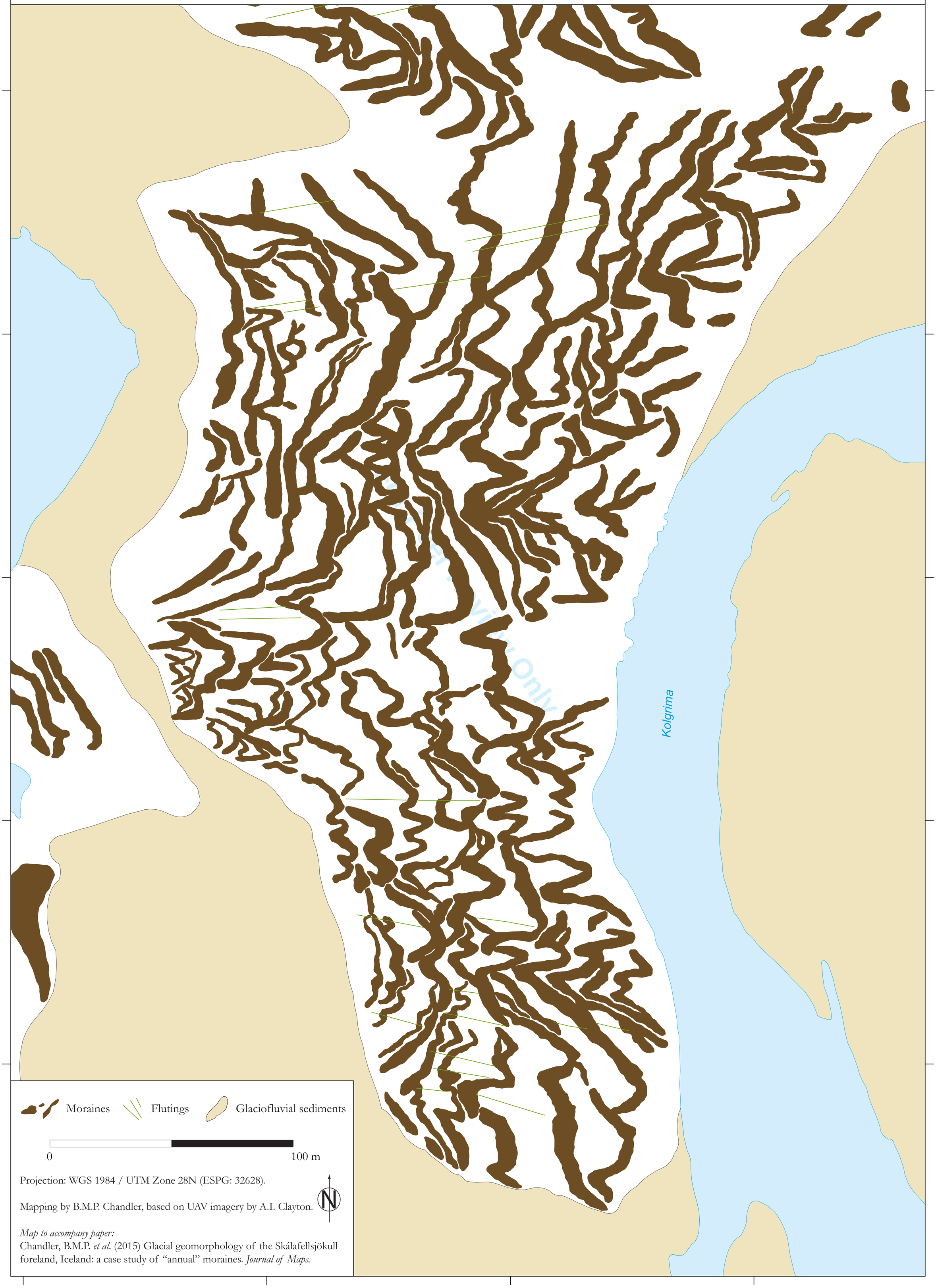

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